Stereo Imaging of Internal Fiducials Indicates Intrafractional Tumor Deformation during CyberKnife SBRT

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Abstract— **In this study, we analyzed fiducial position data of three lung, two liver and one pancreas patients treated by CyberKnife SBRT in order to assess the deformation of moving tumors. Each patient had 4 fiducials implanted in or near the tumor as the surrogates for tracking the tumor. The fiducial positions in 3D were determined based on a pair of orthogonal x-ray images. The centroids of each fiducial in the image pair were first digitized manually and paired. The 3D coordinates of the fiducial was then derived using the geometry of CyberKnife imaging system for real-time tumor tracking. For each patient, about 20 pairs of images were analyzed in time sequence. The sum of the inter-fiducial distances was calculated as a parameter for a surrogate tumor volume, and the tumor volume is assumed proportional to the cube of the sum of the distance based on scaling laws.**

Variations of the calculated surrogate tumor volume were observed for all 6 patients. For one lung tumor in the lower lobe near the chest wall, the tumor volume increased and peaked at the 4th image (2.7%) and decreased to the minimum at the end of treatment (-4.7%). For the other two lung tumors, tumor volumes varied from -4.5 to 3.4% and -4.5 to 1.1%. Relatively smaller volume variations were observed in the two liver tumors (from -1.6 to 2.8% and -3.6 to 3.2%). In the pancreas case, the variation was from -1.8 to 4.1%. Tumor volume variations demonstrated quite different behaviors among different tumor locations and disease sites. In all 3 lung tumors, the volumes tended to decrease near the end of the treatment due to radiation response.

Keywords—**CyberKnife, tumor deformation, fiducial**

I. INTRODUCTION

The efficacy of radiotherapy for thoracic and abdominal tumors is severely compromised by respiratory motion. A large margin to the clinical target volume is required to account for the likely motion and setup uncertainty in conventional radiotherapy treatment for these tumors in order to ensure adequate dose delivery to the target. In recent years, a lot of efforts have been dedicated to study the intrafractional tumor motion based on different imaging modalities for the reduction of the geometric margins. For tumors clearly visible in fluoroscopic videos, automatic or semi-automatic algorithms have been developed to track tumors following breathing motion, yet most of methods are not ready for treating patients in clinic[1]. It is difficult for the algorithms to detect the tumors, especially when the tumors are heavily occluded and obscured by the nearby normal organs. To achieve successful tumor tracking, radiopaque fiducials are often implanted near in or near the tumor as surrogates for rigid tumor motion [2]-[4].

The non-rigid or deformable component of the tumor motion during radiotherapy has been rarely studied. Xie et al. reported both rigid and non-rigid intrafractional tumor motion during CyberKnife (Accuray, Sunnyvale, CA) based hypofractionated treatment of the prostate cancer [5]. The Rigid Body Error (RBE) reported by the system was used to evaluate deformation of the prostate during treatment. However, RBE only reported the distance that the fiducial had deviated from the original position but did not provide any directional information, which is crucial to estimate target volume variation. King et al. reported inter-fractional volume variations of the prostate based on the correlation between the prostate volume and inter-transponders distance using the Calypso system[6]. Although the system is capable of real-time monitoring of 3D transponder movements using an external electromagnetic array, only the means of inter-transponder distance in certain fractions were reported in their study. Lu et al. investigated tumor deformation between the end of inhale (EOI) and exhale (EOE) for 12 lung and

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5 upper abdominal lesions under hypofractionated radiotherapy [7]. The Clinical Target Volume (CTV) was consistently delineated by the physicians in two CTs from EOI and EOE. The CTVs from two phases were aligned based on implanted fiducials to evaluate potential missing coverage of the target. It was concluded that 3 mm margin was required to compensate for the tumor deformation between EOI and EOE for lung lesions and the margin required might be larger in the upper abdominal lesions. In this study, the tumor deformation occurred in other phases was not evaluated. Since the study was based on two CTs, the tumor radiation response, which might cause significant tumor volume variation, especially because of hypofractionated radiotherapy, was not evaluated. Overall, the intrafractional tumor deformation is difficult to study and it is far more from being well understood. In CyberKnife based hypofractionated radiotherapy, X-ray images were taken between beam deliveries through two orthogonal flat-panel X-ray imaging systems to verify tumor localization. This study was aimed at reconstructing 3D fiducial locations based on 2D fiducials in two orthogonal X-ray images and further using 3D fiducials as surrogates to monitor infractional tumor deformation for patients with lung and upper abdominal lesions.

II. METHOD AND MATERIALS

The CyberKnife system is capable of real-time tracking of the moving tumor during treatment. The image guidance is provided by two orthogonal X-ray imaging systems designed without being blocked by the LINAC head. Two X-ray sources are installed at the ceiling, pointing 45° toward the Align-center (Fig. 1). The flat panel detectors lie horizontally underneath the floor. The sources have collimators in trapezoidal shape with the wide side at the bottom of the collimators. After proper image warping, the live X-ray images can be reconstructed at a virtual detector plane, which is perpendicular to the source. During treatment, X-ray images are taken simultaneously from two orthogonal detectors and further processed to verify the real-time tumor location.

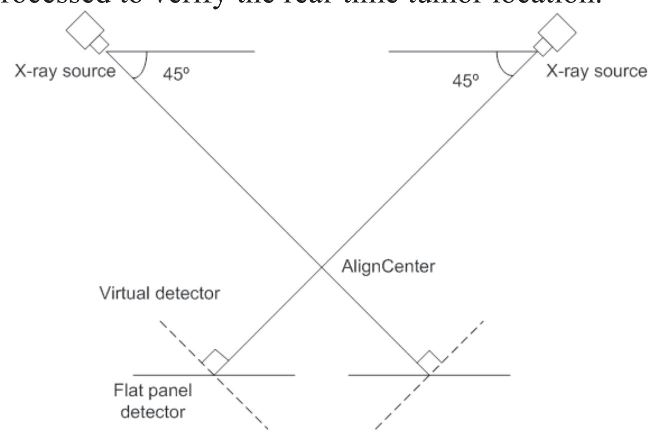

Fig. 1 The geometry of the imaging system.

Three lung, two liver and one pancreas patients with 4 fiducials implanted were selected in this study. The patients were treated in Synchrony mode, thus the fiducial positions can be correlated to respiratory phases. For each patient, about 20 pairs of X-ray images (from before to the end of treatment) were analyzed in time sequence. In each X-ray image pair, the centroids of the 4 fiducials were first manually determined and paired. For each pair of the fiducials, the 2D coordinates in the two X-ray images are thus known. Based on known distances between the sources to the align-center and align-center to the panels, the 3D coordinates of the fiducial can be derived based on stereo imaging technique. The stereo imaging technique is well developed to achieve 3D coordinates of the object based on the disparity from different view angles. After 3D fiducial locations were determined, the sum of the inter-fiducial distances was calculated as the indication of the tumor volume. Based on scaling laws, the volume of the tumor was proportional to the cube of the sum of this distance. After the tumor volume before treatment was selected as the baseline, the percentage tumor volume variations as the indicator of the tumor deformation were calculated for all the X-ray image pairs.

III. Results and discussion

For all 6 patients, the plotted curves of tumor volume variations demonstrated periodic and/or drifting behavior due to breathing or/and radiation response. For the patient with lung tumor in the lower lobe near the chest wall, the tumor volume increased and reached the peak at 4th image (2.7%) and decreased and reached the bottom at the end of treatment (-4.7%) (Fig. 2). For the other two lung patients in mediastinal region, tumor volumes varied periodically from -4.5 to 3.4% and -4.5 to 1.1%, respectively. Relatively smaller tumor volume variations were observed in the two liver patients (from -1.6 to 2.8% and -3.6 to 3.2%). The curve from one liver patient demonstrated slow increasing or upward drifting behavior. In the pancreas case, the periodic variation was from -1.8 to 4.1%. In overall, intrafractional tumor volume variations were quite different for different tumor locations and disease sites. For all 3 lung tumors, the tumor volumes tended to decrease along with treatment time due to radiation response.

Currently, there are two main factors that hinder the study on intrafractional tumor deformation, namely the imaging capability during treatment and 3D tumor shape reconstruction. Since volumetric imaging of the patient during treatment is currently not feasible, projection X-ray imaging in two views is a compromise of imaging time and required anatomy information. However, the information in the projection X-ray images is not sufficient to reconstruct the anatomy of interest in 3D. Therefore fiducials or other surrogates are needed to obtain volumetric anatomy information. In this study, we correlate the 3D distance between the fiducials to the tumor volume. This correlation may not be built with full confidence as the results may depend on the location of the fiducials. In our study, the majority of the fiducials are implanted in or very close to the tumor. The correlation between the fiducial and 3D tumor shape needs to be further explored in future studies with more patient data.

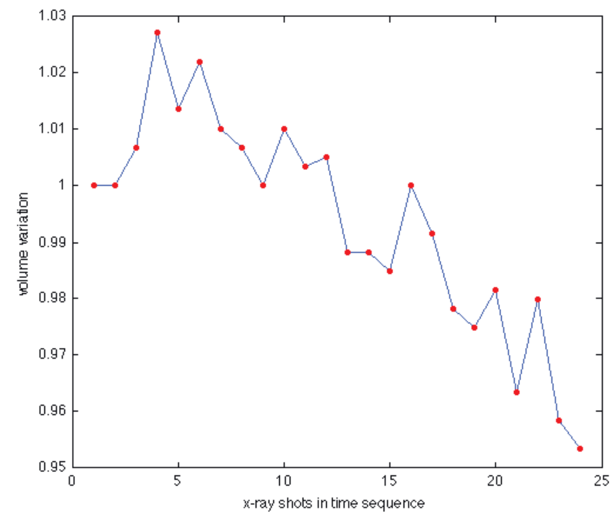

Fig. 2 Tumor volume variation for a lung cancer patient.

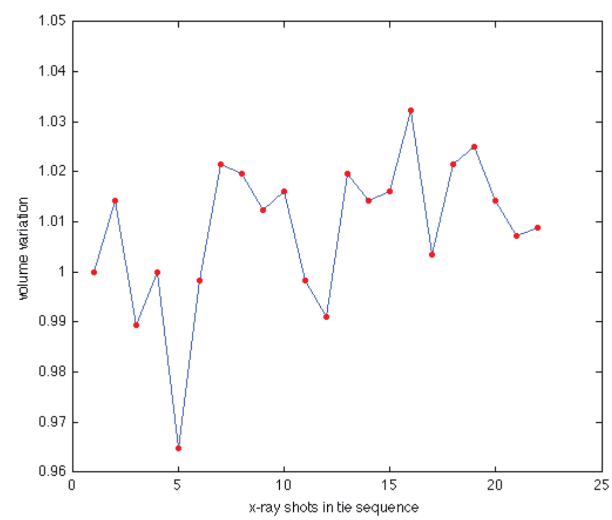

Fig. 3 Tumor volume variation for a liver cancer patient.

IV. CONCLUSIONS

Studies of intrafrational tumor volume variations are rare due to limited imaging guidance during treatment. However, such variations could provide valuable information to estimate tumor margin expansion, guide dosimetric planning and determine adaptive treatment scheme. The assumption made in this study, that fiducial location variation represented tumor volume variation, is also widely used in current fiducial based CyberKnife treatment of moving tumors. Further population based and site-specific studies are critical to understand whether tumor volume variations are caused by breathing or due to tumor radiation response.

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